

A Massive Substellar Companion to the Massive Giant HD 119445

Masashi OMIYA,¹ Hideyuki IZUMIURA,^{2,3} Inwoo HAN,⁴ Byeong-Cheol LEE,^{4,5}
Bun'ei SATO,⁶ Eiji KAMBE,² Kang-Min KIM,⁴ Tae Seog YOON,⁵ Michitoshi YOSHIDA,²
Seiji MASUDA,⁷ Eri TOYOTA,⁸ Seitaro URAKAWA,⁹ and Masahide TAKADA-HIDAI,¹⁰

¹*Department of Physics, Tokai University, 1117 Kitakaname, Hiratsuka, Kanagawa 259-1292, Japan*
ohmiya@peacock.rh.u-tokai.ac.jp

²*Okayama Astrophysical Observatory, National Astronomical Observatory of Japan, Asakuchi,
Okayama 719-0232, Japan*

³*Department of Astronomical Science, The Graduate University for Advanced Studies, Shonan
Village, Hayama, Kanagawa 240-0193, Japan*

⁴*Korea Astronomy and Space Science Institute, 61-1 Whaam-dong, Youseong-gu, Taejeon 305-348,
South Korea*

⁵*Department of Astronomy and Atmospheric Sciences, Kyungpook National University, Daegu
702-701, South Korea*

⁶*Global Edge Institute, Tokyo Institute of Technology, 2-12-1-S6-6 Ookayama, Meguro-ku, Tokyo
152-8550, Japan*

⁷*Tokushima Science Museum, Asutamu Land Tokushima, Itano-gun, Tokushima 779-0111, Japan*

⁸*Kobe Science Museum, 7-7-6 Minatojimanakamachi, Chuo-ku, Kobe, Hyogo 650-0046, Japan*

⁹*Bisei Spaceguard Center, Japan Spaceguard Association, 1716-3 Okura, Bisei-cho, Ibara, Okayama
714-1411, Japan*

¹⁰*Liberal Arts Education Center, Tokai University, 1117 Kitakaname, Hiratsuka, Kanagawa
259-1292, Japan*

(Received 0 0; accepted 0 0)

Abstract

We detected a brown dwarf-mass companion around the intermediate-mass giant star HD 119445 (G6III) using the Doppler technique. This discovery is the first result from a Korean–Japanese planet search program based on precise radial velocity measurements. The radial velocity of this star exhibits a periodic Keplerian variation with a period, semi-amplitude and eccentricity of 410.2 days, 413.5 m s^{−1} and 0.082, respectively. Adopting a stellar mass of 3.9 M_{\odot} , we were able to confirm the presence of a massive substellar companion with a semimajor axis of 1.71 AU and a minimum mass of 37.6 M_J , which falls in the middle of the brown dwarf-mass region. This substellar companion is the most massive ever discovered within 3 AU of a central

intermediate-mass star. The host star also ranks among the most massive stars with substellar companions ever detected by the Doppler technique. This result supports the current view of substellar systems that more massive substellar companions tend to exist around more massive stars, and may further constrain substellar system formation mechanisms.

Key words: stars: individual (HD 119445)—star: low-mass, brown dwarfs—techniques: radial velocities

1. Introduction

A brown dwarf is defined as an object that has a mass between the deuterium-burning limit of $\sim 13 M_J$ and the hydrogen-burning limit of $\sim 80 M_J$ (e.g., Burrows et al. 1997). So far, brown dwarf-mass companions to normal stars have been searched for by various techniques, such as precise Doppler measurements (e.g., Nidever et al. 2002; Patel et al. 2007), direct imaging (e.g., McCarthy & Zuckerman 2004; Lafrenière et al. 2007), spectroscopic (e.g., Neuhäuser & Guenther 2004) and astrometric observations (e.g., Halbwachs et al. 2000; Zucker & Mazeh 2001). Although some brown dwarf-mass companions have been detected by these methods, one intriguing result from these observations is that brown dwarf-mass companions close ($\lesssim 1000$ AU) to solar-type stars are conspicuously scarce compared to planetary and stellar companions (e.g., Gizis et al. 2001; McCarthy & Zuckerman 2004). From the combined results of various precise Doppler surveys of nearby FGK-type stars, Grether & Lineweaver (2006) reported that less than 1 % of solar-type stars harbor brown dwarf-mass companions with orbital periods less than 5 years, while 11 ± 3 % and 5 ± 2 % have stellar companions and giant planets, respectively. Moreover, according to a near-infrared imaging survey of the Sco OB2 association by Kouwenhoven et al. (2007), the frequency of brown dwarf-mass companions ($\gtrsim 30 M_J$) with orbital separations of 130–520 AU around intermediate-mass A or late-B type stars is 0.5 ± 0.5 %. This rate is lower than that of stellar companions by one order of magnitude. The paucity of brown dwarf-mass companions relative to both planetary companions and stellar companions is known as a “brown dwarf desert” (e.g., Marcy & Butler 2000; Grether & Lineweaver 2006). The existence of the desert may be explained by orbital migration (Armitage & Bonnell 2002) or ejection (Reipurth & Clarke 2001) of brown dwarf-mass companions, or may suggest a bimodal mass function of substellar companions that could be produced by two distinct formation mechanisms: core-accretion in protoplanetary disks (e.g., Ida & Lin 2004; Alibert et al. 2005), forming mostly planetary companions, and gravitational fragmentation in molecular clouds or protoplanetary disks (e.g., Boss 1997; Bate 2000; Rice et al. 2003; Stamatellos & Whitworth 2009), forming mostly stellar or brown dwarf-mass companions.

To date, several precise Doppler surveys of subgiants, giants and early-type dwarfs have

uncovered four brown dwarf-mass companions ($13 M_J < M_2 \sin i_p \leq 25 M_J$) and 21 planetary companions ($0.6 M_J \leq M_2 \sin i_p \leq 13 M_J$) around intermediate-mass stars ($1.5 M_\odot \leq M \leq 5 M_\odot$) (Sato et al. 2003; Hatzes et al. 2005; Setiawan et al. 2005; Galland et al. 2006; Hatzes et al. 2006; Johnson et al. 2007; Lovis & Mayor 2007; Niedzielski et al. 2007; Robinson et al. 2007; Sato et al. 2007; Johnson et al. 2008; Liu et al. 2008, Sato et al. 2008a, 2008b; Liu et al. 2009; Niedzielski et al. 2009). Preliminary statistics suggest that some properties of substellar systems orbiting intermediate-mass stars are not necessarily similar to those of solar-type stars (e.g., Butler et al. 2006). The masses of substellar companions orbiting intermediate-mass stars tend to be larger than those around solar-type stars (Lovis & Mayor 2007; Hekker et al. 2008). The orbital semimajor axes of all substellar companions detected around intermediate-mass giants are larger than about 0.6 AU (Johnson et al. 2007; Sato et al. 2008a; Niedzielski et al. 2009). In comparison, substellar companions of solar-type stars can also be found in much closer orbits (≥ 0.017 AU). The metallicity [Fe/H] of many planet-harboring intermediate-mass stars is lower than that typically observed for solar-type stars with planetary companions (Fischer & Valenti 2005; Pasquini et al. 2007; Takeda et al. 2008). Additional comparisons between planetary systems orbiting intermediate-mass stars and other types of stars would be of great interest for better understanding the dependence of substellar system formation on the central star mass.

We report the discovery of a brown dwarf-mass companion orbiting the intermediate-mass giant HD 119445. This is the first result of an ongoing Korean–Japanese planet search program carried out at Bohyunsan Optical Astronomy Observatory (BOAO, Korea) and Okayama Astrophysical Observatory (OAO, Japan). The planet search program is introduced in section 2. We describe the properties of the host star and the orbital motion in sections 3 and 4. The cause of the radial velocity variation and an upper limit on the companion mass are discussed in section 5. In section 6, we consider the implications of this discovery for the current picture of substellar companions.

2. Korean–Japanese Planet Search Program

In 2005, we started a joint planet search program between Korean and Japanese researchers to search for planets around GK-type giant stars using a precise Doppler technique with using the 1.8-m telescope at BOAO and the 1.88-m telescope at OAO. This survey program is an extended version of the ongoing OAO planet search program (Sato et al. 2005) and part of an international collaboration among researchers from Korea, China and Japan (an East-Asian Planet Search Network, EAPS-Net; Izumiura 2005). The collaboration aims at clarifying the properties of planetary systems around intermediate-mass stars by surveying more than 800 GK giants for planets at OAO, BOAO, the Xinglong station (China), and the Subaru Telescope.

For the Korean–Japanese planet search program, we selected about 190 target stars

from the *Hipparcos* catalog based on the following criteria: color-index $0.6 < B - V < 1.0$, absolute magnitude $-3 < M_v < 2$, declination $\delta > -25^\circ$, and visual magnitude $6.2 < V < 6.5$. These targets are fainter than those of the OAO and Xinglong program (Sato et al. 2005; Liu et al. 2008). We divided the targets into two parts: one for BOAO and the other for OAO. Each is observed independently at the assigned observatory, although a star that exhibits a large radial velocity variation is observed intensively at both observatories.

We will also carry out abundance analyses for all the target stars to derive fundamental stellar parameters and chemical compositions, and to investigate correlations between these stellar characteristics and the existence of orbiting planets.

2.1. BOES Observations

Radial velocity observations at BOAO were carried out with the 1.8-m telescope and BOAO Echelle Spectrograph (BOES; Kim et al. 2007), a fiber-fed high resolution echelle spectrograph. For precise radial velocity measurements, we placed an iodine absorption cell (I_2 cell) in the optical path in front of the fiber entrance of the spectrograph (Kim et al. 2002) and used a 200- μm fiber, obtaining a wavelength resolution $R = \lambda/\Delta\lambda \sim 51000$. The spectra covered a wavelength range of 3500–10500 Å. We used the range between 5000 Å and 5900 Å, a region covered by many I_2 absorption lines, for precise radial velocity measurements. We also made use of Ca II H lines at around 3970 Å as chromospheric activity diagnostics. Echelle data reduction was performed using the IRAF¹ software package in the standard manner.

Precise radial velocities for the BOES data were derived using a modeling method detailed in Sato et al. (2002), based on the method of Butler et al. (1996) and improved and optimized for BOES data analysis. We used seven Gaussian profiles with a common full width half maximum of 1.3 pixels, placed at 1 pixel intervals to reconstruct the BOES instrumental profile, and a fourth-order Legendre polynomial to describe the wavelength scale. The number of Gaussians, the width and interval of the Gaussian, and the order of the Legendre polynomial were chosen to minimize the long-term radial velocity dispersion of standard star HD 57727, which is known to have a small radial velocity scatter of $\lesssim 7 \text{ m s}^{-1}$ based on OAO observations over 7 years. We employed the extraction method described in Sato et al. (2002) to prepare a stellar template spectrum from some stellar spectra taken through the I_2 cell (I_2 +stellar spectra). Stellar radial velocity was determined by averaging radial velocities from each of ~ 200 spectral segments (each ~ 5 Å long) except those with the worst least-squares fit. This technique allowed us to achieve a Doppler precision of $\sim 11 \text{ m s}^{-1}$ over 2.3 years during this project (see figure 1).

¹ IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation, USA.

2.2. *HIDES* Observations

Radial velocity observations at OAO were carried out with the 1.88-m telescope and High Dispersion Echelle Spectrograph (HIDES; Izumiura 1999) attached to the coudé focus of the telescope. For radial velocity measurements, we observed over the 5000 to 6200 Å wavelength range with a slit width of 200 μm (0.76") giving a spectral resolution of 63000. An I₂ cell (Kambe et al. 2002) was used for precise wavelength calibration. Echelle data reduction was performed using the IRAF software package in the standard manner. Stellar radial velocities were derived from the I₂-superposed stellar spectrum modeling technique detailed in Sato et al. (2002), and gave a Doppler precision of ~ 7 m s⁻¹ over 2.3 years during our program (see figure 1). We also obtained stellar spectra without the I₂ cell using the same spectrograph setting for abundance analysis.

3. HD 119445 Stellar Parameters

HD 119445 (HR 5160, HIP 66892) is located at 289 pc from the Sun according to the *Hipparcos* parallax of $\pi = 3.46 \pm 0.71$ mas. The star is classified as a G6III giant star with $V = 6.30$ and $B - V = 0.879 \pm 0.004$ (ESA 1997). We derived an effective temperature T_{eff} of the star as $T_{\text{eff}} = 5083 \pm 103$ K using a $(B - V) - T_{\text{eff}}$ calibration of Alonso et al. (1999, 2001). A luminosity of $L = 251 \pm 95 L_{\odot}$ was obtained from the absolute magnitude $M_v = -1.03$ and the bolometric correction $B.C. = -0.23$ based on the calibration of Alonso et al. (1999). A stellar mass of $M = 3.9 \pm 0.4 M_{\odot}$ was estimated by interpolating the evolutionary tracks of Girardi et al. (2000) with the estimated T_{eff} and L . We determined the surface gravity to be $\log g = 2.40 \pm 0.17$ and the stellar radius $R = 20.5 \pm 9.3 R_{\odot}$ from M , L and T_{eff} . A microturbulent velocity $V_t = 1.49 \pm 0.20$ km s⁻¹ and $[\text{Fe}/\text{H}] = 0.04 \pm 0.18$ were derived from abundance analysis with a model atmosphere (Kurucz 1993) using equivalent widths of Fe I and Fe II lines measured from an I₂-free spectrum of HD 119445. We adopted gf-values of Fe I and Fe II lines from Takeda et al. (2005). The stellar rotational velocity $v \sin i_s$ was found by Gray (1989) and de Medeiros & Mayor (1999) to be 6.0 ± 0.6 km s⁻¹ and 6.9 ± 1.0 km s⁻¹, respectively. These values are larger than rotational velocities of most of late G-type giants. The stellar parameters are summarized in table 1.

Figure 2 shows Ca II H lines of HD 119445 and the radial velocity standard star HD 57727. There is a lack of significant emission in the Ca II H line core of HD 119445 and HD 57727, which suggests chromospheric inactivity, although the correlation between chromospheric activity and intrinsic radial velocity jitter for giant stars is not yet well established. Moreover, *Hipparcos* photometry collected from 187 observations of the star demonstrates the photometric stability of HD 119445 down to $\sigma \sim 0.008$ mag, which also suggests chromospheric inactivity for the star.

4. Orbital Solution

We monitored the radial velocity of HD 119445 for 2.3 years from the beginning of the survey at both observatories. We accumulated 9 BOAO data points with a typical signal-to-noise ratio (S/N) of 180 pixel^{-1} , given an exposure time of 900–1200 s, and 27 OAO data points with a typical S/N of 140 pixel^{-1} , given an exposure time of 1200–1800 s. The observed radial velocities of HD 119445 are shown in figure 3 and listed in tables 2 (BOAO) and 3 (OAO), together with estimated uncertainties. The best-fit Keplerian orbit derived from both the BOAO and OAO data has a period $P = 410.2 \pm 0.6$ days, a velocity semi-amplitude $K_1 = 413.5 \pm 2.6 \text{ m s}^{-1}$, and an eccentricity $e = 0.082 \pm 0.007$. The best-fit curve is shown in figure 3 as a solid line overlaid on the observed velocities. We applied an offset of ΔRV , $-43.0 \pm 5.1 \text{ m s}^{-1}$, estimated concurrently with the orbital fit, to the BOAO data points by minimizing χ^2 in fitting a Keplerian model to the combined BOAO and OAO velocity data. The difference in the velocity scales derived from the BOES and HIDES stellar templates yielded the offset. The best-fit parameters and uncertainties are listed in table 4. The uncertainties were estimated by a Monte Carlo approach.

The rms scatter of the residuals to the best-fit is 13.7 m s^{-1} . This value is comparable to the typical radial velocity scatter ($10\text{--}20 \text{ m s}^{-1}$) of the G-type giants (Sato et al. 2005) within the typical measurement errors of $\sim 13 \text{ m s}^{-1}$ (BOAO) and $\sim 9 \text{ m s}^{-1}$ (OAO). Since we did not find any significant periodic variation due to a second companion in the residuals, we conclude that HD 119445 would have no additional substellar companion with a period less than 800 days. Adopting a stellar mass $M = 3.9 \pm 0.4 M_\odot$ for HD 119445, we obtained a semimajor axis $a = 1.71 \pm 0.06 \text{ AU}$ and a minimum mass $M_2 \sin i_p = 37.6 \pm 2.6 M_J$ for a companion. The error of the mass arose mostly from the stellar mass error of the host star.

5. Line Shape Analyses and an Upper Limit of a Mass

The spectral-line shape analyses were performed using techniques described in Sato et al. (2007) to investigate other causes of the apparent radial velocity variation, such as rotational modulation and pulsation. For the analyses, we used two high-resolution stellar templates extracted from I₂+stellar spectra obtained at OAO. One template was constructed from four spectra with observed radial velocities ranging from 330 to 430 m s^{-1} (peak), and the other from four spectra of around -370 m s^{-1} (valley). Cross-correlation profiles of the templates were calculated for 27 spectral segments (4- to $5\text{-}\text{\AA}$ width each) that did not include severely blended lines or broad lines. Three bisector quantities were calculated for the cross-correlation profile of each segment: the velocity span (BVS), which is the velocity difference between two flux levels of the bisector; the velocity curvature (BVC), which is the difference of the velocity span of the upper half and lower half of the bisector; and the velocity displacement (BVD), which is the average of the bisector at three different flux levels. We used flux levels of 25%, 50%, and 75%

of the cross-correlation profile to calculate the above quantities. These bisector quantities for HD 119445 are shown in figure 4. As expected under the planetary hypothesis, both the BVS and BVC (each average to $-7.3 \pm 18.1 \text{ m s}^{-1}$ and $-1.1 \pm 6.2 \text{ m s}^{-1}$, respectively) are essentially identical to zero, meaning that the cross-correlation profiles are symmetric. The dispersions of the BVS and BVD are relatively large. This is probably due to the broad absorption lines in the stellar spectra caused by the large rotational velocity. However, the average value of the BVD ($-766.4 \pm 32.3 \text{ m s}^{-1}$) is consistent with the velocity difference between the two templates. The value is more than 20 times larger than the dispersions; thus, the velocity difference between the templates is considered to be due to a parallel shift of spectral lines caused by orbital motion, not to variations in spectral line shapes. Hence, the observed radial velocity variation of HD 119445 is best explained by orbital motion of a companion not by intrinsic activity such as rotational modulation or pulsation.

If we assume the orbit is randomly oriented, a 12 % chance exists that the true mass exceeds the brown dwarf-mass limit of $80 M_J$ ($i_p \lesssim 28^\circ$). Assuming that the orbit of the companion is coplanar with the stellar equatorial plane, a small orbital inclination of less than 28° implies a stellar rotational velocity larger than 12 km s^{-1} . Single G-type giants with such a high rotational velocity are rare and would be identified as X-ray sources in *ROSAT* observations. However, no X-ray emissions from HD 119445 have been detected (Hunsch et al. 1998), which suggests that the rotational velocity of HD 119445 is not fast and that the orbital inclination i_p is not so small. Thus, the true mass of the companion may be smaller than $80 M_J$, which is the upper-limit mass for a brown dwarf.

6. Discussion

We detected a brown dwarf-mass companion orbiting the intermediate-mass giant star HD 119445. This discovery is the first result from our Korean–Japanese planet search program. The host star HD 119445 has a mass of $3.9 M_\odot$. It is one of the most massive stars hosting substellar companions. HD 119445 b is the fifth brown dwarf-mass companion with a semimajor axis of less than 3 AU and the most massive brown dwarf-mass companion among those discovered around intermediate-mass stars. Now we found two brown dwarf-mass companions and ten planetary companions from the surveys at OAO, Xinglong and BOAO from a total of about 500 targets of the surveys (Sato et al. 2003, 2007, 2008a; 2008b; Liu et al. 2008, 2009; this work). The ratio between the numbers of brown dwarf-mass companions and planetary companions detected from the surveys of our GK-type giants seems comparable to that ($\leq 1\%$ to $\sim 5\%$; Grether & Lineweaver 2006) for solar-type stars, although the surveys are not yet complete and detection limits differ between solar-type and giant stars. This result may support the existence of a brown dwarf desert, a deficit of brown dwarf-mass companions relative to planetary companions, around intermediate-mass stars inside $a \sim 3 \text{ AU}$ orbital separation.

However, the existence of the desert may depend on host star’s mass. In figure 5, we plot

masses of the companions detected within semi-major axis of 3 AU by precise Doppler surveys against their host star’s masses; solar-mass stars ($0.7 M_{\odot} \leq M < 1.5 M_{\odot}$, *open triangles*), intermediate-mass subgiants and giants ($1.5 M_{\odot} \leq M \leq 5 M_{\odot}$, *filled circles*), an intermediate-mass dwarf (A-type star HD 180777, *open circle*), and HD 119445 (*star*) (*The Extrasolar Planets Encyclopadia*²; Halbwachs et al. 2000; Tinney et al. 2001; Nidever et al. 2002; Vogt et al. 2002; Endl et al. 2004; Galland et al. 2006; Liu et al. 2008; Sato et al. 2008a, 2008b; this work). The detectable companion mass for a given host star mass depends on the orbital separation of its companion and the radial velocity jitter of the host star. Assuming that typical radial velocity jitters σ for solar-mass stars, intermediate-mass subgiants ($1.5\text{--}1.9 M_{\odot}$) and giants ($1.9\text{--}5 M_{\odot}$) are $\sim 5 \text{ m s}^{-1}$, $\sim 7 \text{ m s}^{-1}$ and $\sim 20 \text{ m s}^{-1}$, respectively, we estimated the lower limits of companion masses detectable by precise Doppler surveys around a solar-mass star and intermediate-mass subgiant and giant at 3 AU (solid lines in figure 5), corresponding to companion masses that provide the amplitude of three times of typical radial velocity jitters. We also indicate detectable masses for these stars at 0.02 AU (dotted lines) and 0.6 AU (dot-dashed lines), corresponding to the semimajor axes of the known innermost planets orbiting solar-type and intermediate-mass evolved stars.

Two unpopulated regions of substellar companions orbiting intermediate-mass subgiants and giants seem to exist in region (a) and (b)³. A possible host star-companion mass correlation considered from unpopulated region (a) and (b) supports the current view that more massive substellar companions tend to exist around more massive stars, that are derived from the results of planet searches around various mass stars (Lovis & Mayor 2007; Hekker et al. 2008).

All of the brown dwarf-mass companions to intermediate-mass evolved stars were found around those with $\geq 2.7 M_{\odot}$ and there seems to be a paucity of such companions around those with $1.5\text{--}2.7 M_{\odot}$ (region (a) in figure 5). A brown dwarf-mass companion orbiting the A-type dwarf HD 180777 (Galland et al. 2006) is regarded as a unique and interesting one since it populates the region (a). Such early-type dwarfs have larger typical radial velocity jitter σ ($\geq 66 \text{ m s}^{-1}$ for late A-type dwarfs; Lagrange et al. 2009) than that of evolved stars due to more rapid rotation and pulsation, and thus the planet mass distribution in early-type dwarfs is less well defined than that of intermediate-mass evolved stars. Considering the smaller number of survey targets of $\geq 2.7 M_{\odot}$ (e.g., 35 % of the 300 OAO targets; Takeda et al. 2008) compared with that of $1.5\text{--}2.7 M_{\odot}$, frequency of brown dwarf companions may become higher as stellar mass increases. This might favor gravitational instability in protostellar disks (Rice et al. 2003) rather than fragmentation of proto-stellar clouds (Bate 2000) as the formation mechanism of brown dwarf-mass companions because stellar systems with larger difference in mass between primary and secondary stars are more difficult to form by the latter mechanism (Bate 2000).

² <http://exoplanet.eu/>, Version of 24/April/2008

³ We exclude a brown dwarf-mass companion orbiting a possible high mass giant HD 13189 ($M = 4.5 \pm 2.5 M_{\odot}$; Hatzes et al. 2005) from the following discussion because of the large uncertainty in its host star’s mass.

Also, there seems to be a possible paucity of lower-mass companions around $2.4\text{--}4\ M_{\odot}$ stars (region (b) in figure 5). Although it is basically difficult to detect planets around such "noisy" stars with large intrinsic radial velocity variability ($\sigma \sim 20\ \text{m s}^{-1}$), planets with mass $\geq 2.6\text{--}3.3\ M_J$ ($\geq 5.7\text{--}7.4\ M_J$) and $a = 0.6\ \text{AU}$ ($a = 3.0\ \text{AU}$) should be above the current detection limit ($3\ \sigma \sim 60\ \text{m s}^{-1}$). Recently, Kennedy & Kenyon (2008) predicted that the frequency of giant planets has a peak near $3\ M_{\odot}$ stars based on a core accretion scenario taking account of the movement of snow line along the evolution of accretion and the central stars. Moreover, if a formation mechanism works that invokes capturing of solid bodies migrating inward at the inner edge of the inactive magnetorotational instability-dead zone inside of the protoplanetary disk, gas giant planets could be formed efficiently at around $1\ \text{AU}$ around intermediate-mass stars before the planetary disks deplete (Kretke et al. 2009). Increasing the number of known massive planetary companions around massive intermediate-mass stars by further radial velocity surveys would be of great interest to understand the formation mechanisms of giant planets around intermediate-mass stars.

This research was supported as a Korea-Japan Joint Research Project under the Japan-Korea Basic Scientific Cooperation Program between Korea Science and Engineering Foundation (KOSEF) and Japan Society for the Promotion of Science (JSPS). This research is based on data collected at Bohyunsan Optical Astronomy Observatory (BOAO) that is operated by Korea Astronomy and Space Science Institute (KASI) and Okayama Astrophysical Observatory (OAO) that is operated by National Astronomical Observatory of Japan (NAOJ). We gratefully acknowledge the support from the staff members of BOAO and OAO during the observations. BCL acknowledges the support from the Astrophysical Research Center for the Structure and Evolution of the Cosmos (ARCSEC, Sejong University) of the Korea Science and Engineering Foundation (KOSEF) through the Science Research Center (SRC) program. Data analysis was in part carried out on gsbh computer system operated by the Astronomical Data Center (ADC) and Subaru Telescope of NAOJ. This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France.

References

- Alibert, Y., Mordasini, C., Benz, W., & Winisdoerffer, C. 2005, *A&A*, 434, 343
Alonso, A., Arribas, S., & Martínez-Roger, C. 1999, *A&AS*, 140, 261
Alonso, A., Arribas, S., & Martínez-Roger, C. 2001, *A&A*, 376, 1039
Armitage, P. J., & Bonnell, I. A. 2002, *MNRAS*, 330, L11
Bate, M. R. 2000, *MNRAS*, 314, 33
Boss, A. P. 1997, *Science*, 276, 1836
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanji, P., & Vogt, S. S. 1996, *PASP*, 108, 500

- Butler, R. P., et al. 2006, *ApJ*, 646, 505
- Burrows, A., et al. 1997, *ApJ*, 491, 856
- de Medeiros, J. R., & Mayor, M. 1999, *A&AS*, 139, 433
- Endl, M., Hatzes, A. P., Cochran, W. D., McArthur, B., Allende Prieto, C., Paulson, D. B., Guenther, E., & Bedalov, A. 2004, *ApJ*, 611, 1121
- ESA. 1997, *The Hipparcos and Tycho Catalogues* (ESA SP-1200; Noordwijk: ESA)
- Fischer, D. A., & Valenti, J. 2005, *ApJ*, 622, 1102
- Galland, F., Lagrange, A.-M., Udry, S., Beuzit, J.-L., Pepe, F., & Mayor, M. 2006, *A&A*, 452, 709
- Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, *A&AS*, 141, 371
- Gizis, J. E., Kirkpatrick, J. D., Burgasser, A., Reid, I. N., Monet, D. G., Liebert, J., & Wilson, J. C. 2001, *ApJL*, 551, L163
- Gray, D. F. 1989, *ApJ*, 347, 1021
- Grether, D., & Lineweaver, C. H. 2006, *ApJ*, 640, 1051
- Halbwachs, J. L., Arenou, F., Mayor, M., Udry, S., & Queloz, D. 2000, *A&A*, 355, 581
- Hatzes, A. P., Guenther, E. W., Endl, M., Cochran, W. D., Döllinger, M. P., & Bedalov, A. 2005, *A&A*, 437, 743
- Hatzes, A. P., et al. 2006, *A&A*, 457, 335
- Hekker, S., Snellen, I. A. G., Aerts, C., Quirrenbach, A., Reffert, S., & Mitchell, D. S. 2008, *A&A*, 480, 215
- Hunsch, M., Schmitt, J. H. M. M., & Voges, W. 1998, *A&AS*, 127, 251
- Ida, S., & Lin, D. N. C. 2004, *ApJ*, 604, 388
- Izumiura, H. 1999, in *Proc. 4th East Asian Meeting on Astronomy*, ed. P.S. Chen (Kunming: Yunnan Observatory), 77
- Izumiura, H. 2005, *Journal of Korean Astronomical Society*, 38, 81
- Johnson, J. A., et al. 2007, *ApJ*, 665, 785
- Johnson, J. A., Marcy, G. W., Fischer, D. A., Wright, J. T., Reffert, S., Kregenow, J. M., Williams, P. K. G., & Peek, K. M. G. 2008, *ApJ*, 675, 784
- Kambe, E., et al. 2002, *PASJ*, 54, 865
- Kennedy, G. M., & Kenyon, S. J. 2008, *ApJ*, 673, 502
- Kim, K.-M., et al. 2002, *Journal of Korean Astronomical Society*, 35, 221
- Kim, K.-M., et al. 2007, *PASP*, 119, 1052
- Kouwenhoven, M. B. N., Brown, A. G. A., & Kaper, L. 2007, *A&A*, 464, 581
- Kretke, K. A., Lin, D. N. C., Garaud, P., & Turner, N. J. 2009, *ApJ*, 690, 407
- Kurucz, R. 1993, *ATLAS9 Stellar Atmosphere Programs and 2 km/s grid*. Kurucz CD-ROM No. 13. Cambridge, Mass.: Smithsonian Astrophysical Observatory, 1993., 13,
- Lagrange, A.-M., Desort, M., Galland, F., Udry, S., & Mayor, M. 2009, *A&A*, 495, 335
- Lafrenière, D., et al. 2007, *ApJ*, 670, 1367
- Liu, Y.-J., et al. 2008, *ApJ*, 672, 553
- Liu, Y.-J., Sato, B., Zhao, G., & Ando, H. 2009, *Research in Astronomy and Astrophysics*, 9, 1
- Lovis, C., & Mayor, M. 2007, *A&A*, 472, 657
- Marcy, G. W., & Butler, R. P. 2000, *PASP*, 112, 137

- McCarthy, C., & Zuckerman, B. 2004, *AJ*, 127, 2871
- Neuhäuser, R., & Guenther, E. W. 2004, *A&A*, 420, 647
- Nidever, D. L., Marcy, G. W., Butler, R. P., Fischer, D. A., & Vogt, S. S. 2002, *ApJS*, 141, 503
- Niedzielski, A., et al. 2007, *ApJ*, 669, 1354
- Niedzielski, A., Goździewski, K., Wolszczan, A., Konacki, M., Nowak, G., & Zieliński, P. 2009, *ApJ*, 693, 276
- Pasquini, L., Döllinger, M. P., Weiss, A., Girardi, L., Chavero, C., Hatzes, A. P., da Silva, L., & Setiawan, J. 2007, *A&A*, 473, 979
- Patel, S. G., Vogt, S. S., Marcy, G. W., Johnson, J. A., Fischer, D. A., Wright, J. T., & Butler, R. P. 2007, *ApJ*, 665, 744
- Reipurth, B., & Clarke, C. 2001, *AJ*, 122, 432
- Rice, W. K. M., Armitage, P. J., Bonnell, I. A., Bate, M. R., Jeffers, S. V., & Vine, S. G. 2003, *MNRAS*, 346, L36
- Robinson, S. E., et al. 2007, *ApJ*, 670, 1391
- Sato, B., Kambe, E., Takeda, Y., Izumiura, H., & Ando, H. 2002, *PASJ*, 54, 873
- Sato, B., et al. 2003, *ApJL*, 597, L157
- Sato, B., Kambe, E., Takeda, Y., Izumiura, H., Masuda, S., & Ando, H. 2005, *PASJ*, 57, 97
- Sato, B., et al. 2007, *ApJ*, 661, 527
- Sato, B., et al. 2008a, *PASJ*, 60, 539
- Sato, B., et al. 2008b, *PASJ*, 60, 1317
- Setiawan, J., et al. 2005, *A&A*, 437, L31
- Stamatellos, D., & Whitworth, A. P. 2009, *MNRAS*, 392, 413
- Takeda, Y., Ohkubo, M., Sato, B., Kambe, E., & Sadakane, K. 2005, *PASJ*, 57, 27
- Takeda, Y., Sato, B., & Murata, D. 2008, *PASJ*, 60, 781
- Tinney, C. G., Butler, R. P., Marcy, G. W., Jones, H. R. A., Penny, A. J., Vogt, S. S., Apps, K., & Henry, G. W. 2001, *ApJ*, 551, 507
- Vogt, S. S., Butler, R. P., Marcy, G. W., Fischer, D. A., Pourbaix, D., Apps, K., & Laughlin, G. 2002, *ApJ*, 568, 352
- Zucker, S., & Mazeh, T. 2001, *ApJ*, 562, 549

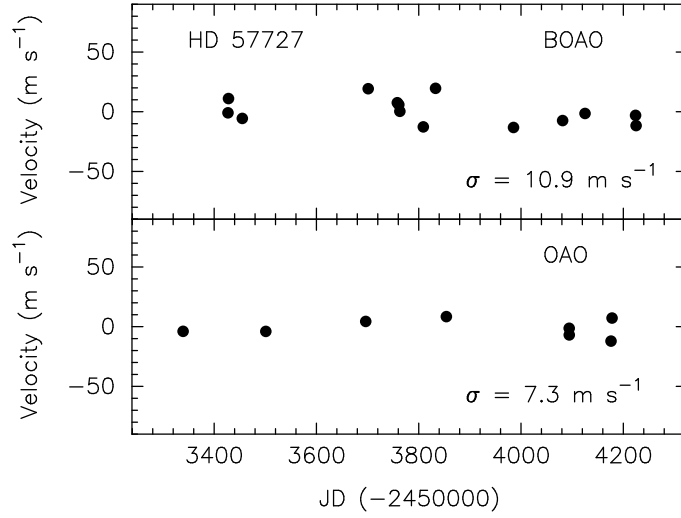


Fig. 1. Radial velocity variations of radial velocity standard star HD 57727 observed at BOAO (upper) and OAO (lower).

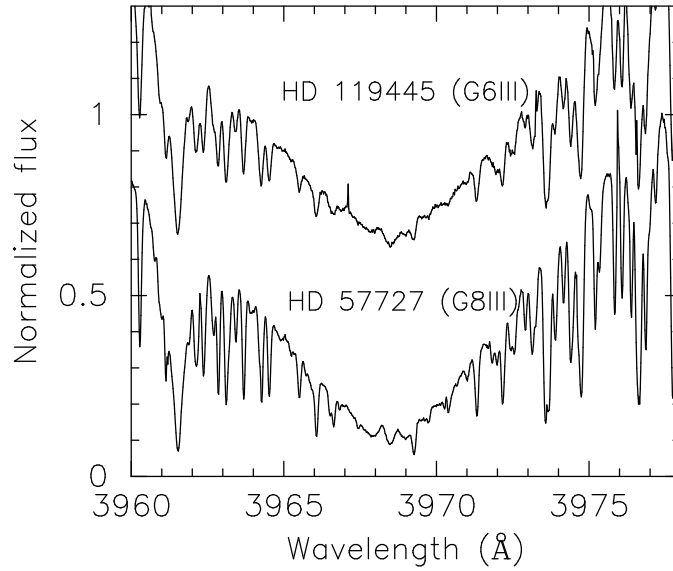


Fig. 2. The spectral region around Ca II H lines of HD 119445 and HD 57727. The Ca II H line of HD 119445 does not seem to exhibit high activity, similar to the line of HD 57727.

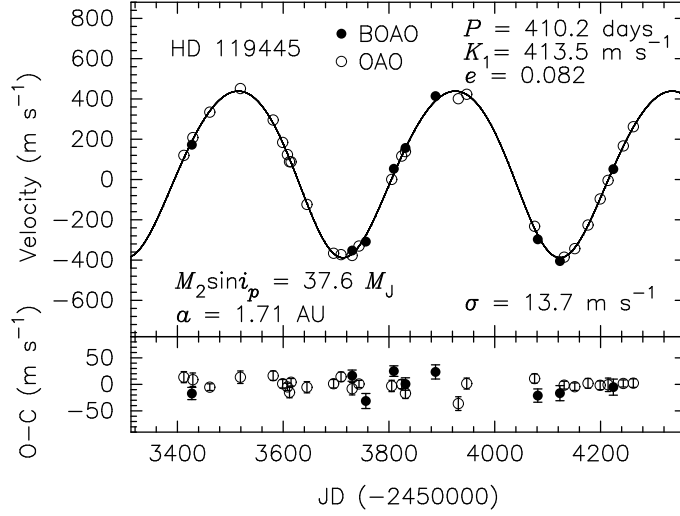


Fig. 3. Upper panel: radial velocities of HD 119445 observed at BOAO (*filled circles*) and OAO (*open circles*). The Keplerian orbital curve we determined is shown by the solid line. Lower panel: Residuals to the best Keplerian fit.

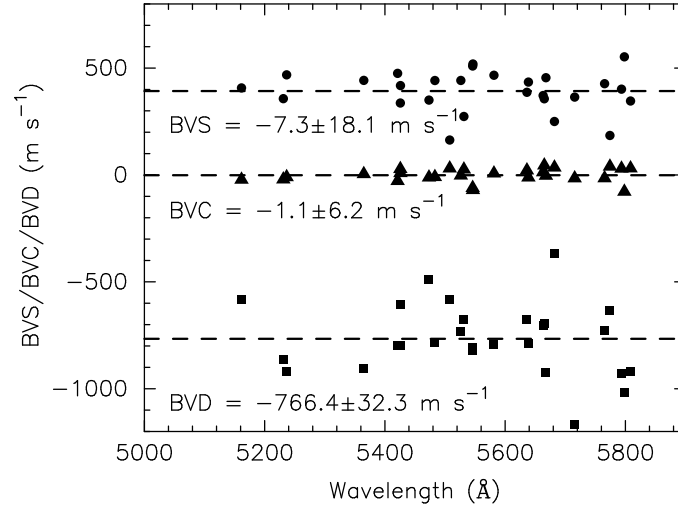


Fig. 4. Bisector quantities calculated by cross-correlation profiles between the stellar templates of HD 119445 at peak ($300\text{--}400$ m s^{-1}) and valley (-400 m s^{-1}) phases of the radial velocities. Shown are the bisector velocity span with an offset of 400 m s^{-1} (BVS, *circles*), bisector velocity curvature (BVC, *triangles*) and bisector velocity displacement (BVD, *squares*). Average values and standard errors are shown in the figure. Dashed lines represent mean values.

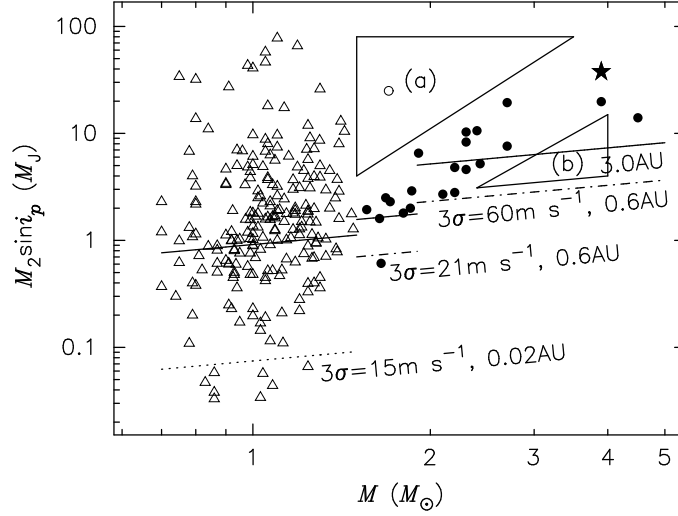


Fig. 5. Primary star masses versus masses of substellar companions orbiting within 3 AU. *Open triangles*, *filled circles* and an *open circle* represent companions orbiting solar-mass stars, intermediate-mass evolved stars (subgiants and giants) and an intermediate-mass dwarf (A-type star; HD 180777), respectively. A *star* represents the HD 119445 system. Solid lines indicate the detection limits for the mass of companions orbiting at 3 AU, corresponding to three times of typical radial velocity jitters σ of 5 m s^{-1} for solar-mass stars ($0.7 M_{\odot} \leq M < 1.5 M_{\odot}$), 7 m s^{-1} for intermediate-mass subgiants ($1.5 M_{\odot} \leq M \leq 1.9 M_{\odot}$) and 20 m s^{-1} for intermediate-mass giants ($1.9 M_{\odot} < M \leq 5 M_{\odot}$). Dotted and dot-dashed lines indicate the detection limits for companions at 0.02 AU and 0.6 AU in solar mass stars and intermediate-mass evolved stars, respectively. Two regions devoid of substellar companions are denoted by (a) and (b).

Table 1. Stellar parameters of the host star HD 119445

Parameter	Value
Spectral Type	G6III
V	6.30
$B - V$	0.879 ± 0.004
π (mas)	3.46 ± 0.71
M_v	-1.03
$B.C.$	-0.23
T_{eff} (K)	5083 ± 103
L (L_{\odot})	251 ± 95
M (M_{\odot})	3.9 ± 0.4
R (R_{\odot})	20.5 ± 9.3
$\log g$	2.40 ± 0.17
V_t (km s^{-1})	1.49 ± 0.20
[Fe/H]	0.04 ± 0.18
$v \sin i_s$ (km s^{-1})	$6.0 \pm 0.6^*$, $6.9 \pm 1.0^{\dagger}$

*Gray (1989)

 \dagger de Medeiros & Mayor (1999)**Table 2.** Radial velocities of HD 119445 at BOAO

JD	Radial velocity	Error
(-2450000)	(m s^{-1})	(m s^{-1})
3427.3555	215.5	11.6
3730.3782	-309.5	10.6
3756.3179	-265.1	14.2
3809.2236	96.3	9.9
3831.2419	199.7	11.7
3888.0653	457.1	13.3
4081.3558	-253.9	12.6
4123.2218	-361.9	14.3
4224.1335	94.5	15.2

Table 3. Radial velocities of HD 119445 at OAO

JD (−2450000)	Radial velocity (m s ^{−1})	Error (m s ^{−1})
3412.2214	119.9	10.5
3429.1852	208.0	12.6
3461.2184	334.6	6.3
3519.0496	451.6	11.8
3581.0147	295.5	8.9
3598.9982	184.2	8.0
3607.9722	123.7	6.8
3611.9573	88.0	10.3
3614.9515	87.7	7.1
3644.9092	−123.8	10.6
3695.3348	−366.1	8.0
3709.3600	−373.1	8.9
3730.3545	−377.2	11.7
3743.3350	−330.3	6.8
3805.1203	0.4	10.7
3824.1283	116.4	8.4
3831.1425	138.5	9.7
3931.1190	401.2	12.9
3947.0120	423.0	10.3
4075.2883	−232.4	8.7
4131.2517	−385.6	7.4
4151.2616	−343.3	7.0
4176.2334	−225.9	9.2
4199.2797	−96.4	8.1
4214.1939	−4.2	12.8
4243.0711	166.6	6.6
4261.9704	262.2	8.0

Table 4. Orbital parameters of HD 119445 b

Parameter	Value
K_1 (m s ⁻¹)	413.5 ± 2.6
P (days)	410.2 ± 0.6
e	0.082 ± 0.007
ω (deg)	160.5 ± 4.3
T (JD)	2452873.9 ± 5.6
ΔRV^* (m s ⁻¹)	-43.0 ± 5.1
rms (m s ⁻¹)	13.7
Reduced $\sqrt{\chi^2}$	1.7
N_{obs}	36
$a_1 \sin i_p$ (10 ⁻³ AU)	15.54 ± 0.10
$f_1(m)$ (10 ⁻⁷ M_\odot)	29.75 ± 0.58
$M_2 \sin i_p$ (M_J)	37.6 ± 2.6
a (AU)	1.71 ± 0.06

*Offset between BOAO and OAO velocities.